

2018-10

Rising levels of temperature and CO₂ antagonistically affect phytoplankton primary productivity in the South China Sea.

Zhang, Y

<http://hdl.handle.net/10026.1/12579>

10.1016/j.marenvres.2018.08.011

Marine Environmental Research

Elsevier

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.

Rising levels of temperature and CO₂ antagonistically affect phytoplankton primary productivity in the South China Sea

Yong Zhang¹, Tifeng Wang¹, He Li¹, Nanou Bao¹, Jason M. Hall-Spencer^{1,3,4}, Kunshan Gao^{1,2*}

¹State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen 361005, China

²Laboratory for Marine Ecology and Environmental Science, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266071, China

³Marine Biology and Ecology Research Centre, University of Plymouth, United Kingdom

⁴Shimoda Marine Research Centre, University of Tsukuba, Japan

Running head: Temperature and CO₂ on primary productivity

*Corresponding author: State Key Laboratory of Marine Environmental Science and College of Ocean and Earth Sciences, Xiamen University, Xiamen 361005, China

E-mail address: ksgao@xmu.edu.cn

23 ABSTRACT

24 Coastal and offshore waters in the South China Sea are warming and becoming
25 acidified due to rising atmospheric levels of carbon dioxide (CO₂), yet the combined
26 effects of these two stressors are poorly known. Here, we carried out shipboard
27 incubations at ambient (398 μ atm) and elevated (934 μ atm) pCO₂ at in situ and in
28 situ+1.8 °C temperatures and we measured primary productivity at two coastal and
29 two offshore stations. Both warming and increased CO₂ levels individually increased
30 phytoplankton productivity at all stations, but the combination of high temperature
31 and high CO₂ did not, reflecting an antagonistic effect. Warming decreased Chl *a*
32 concentrations in off-shore waters at ambient CO₂, but had no effect in the coastal
33 waters. The high CO₂ treatment increased night time respiration in the coastal
34 waters at ambient temperatures. Our findings show that phytoplankton assemblage
35 responses to rising temperature and CO₂ levels differ between coastal and offshore
36 waters. While it is difficult to predict how ongoing warming and acidification will
37 influence primary productivity in the South China Sea, our data imply that predicted
38 increases in temperature and pCO₂ will not boost surface phytoplankton primary
39 productivity.

40
41 *Keywords:* Chl *a*; night time respiration; ocean acidification; ocean warming;
42 primary productivity; South China Sea

1. Introduction

Rising atmospheric carbon dioxide (CO₂) concentrations are warming and acidifying the oceans worldwide (Caldeira and Wickett, 2003; IPCC, 2014), including the South China Sea (Ji et al., 2017). On average, surface seawater temperatures are projected to increase by 1.51–3.22 °C by the end of this century and CO₂ levels to increase from the current level of about 400 µatm up to 1000 µatm (Boyd et al., 2015). Ocean warming and acidification are expected to affect the physiology, distribution and structure of phytoplankton communities (Hare et al., 2007; Feng et al., 2009; Taucher et al., 2012; Sommer et al., 2015; Riebesell et al., 2017).

Rising CO₂ levels can increase the availability of dissolved inorganic carbon (DIC) for phytoplankton carbon fixation, but they are also causing seawater acidification, and this may inhibit algal calcification and photosynthetic carbon fixation (Falkowski and Raven, 2007; Gao and Zheng, 2010; Gao et al., 2012; Brodie et al., 2014). Thus, algal responses to increasing CO₂ levels are dependent on the balance between the positive effects of increasing DIC and the negative effects of decreasing pH (Wu et al., 2008; Bach et al., 2015; Liu et al., 2017). Several studies report that, in comparison to current CO₂ levels, elevated CO₂ (800–1000 µatm) increases productivity of phytoplankton assemblages that are dominated by diatoms (Kim et al., 2006; Tortell et al., 2008; Domingues et al. 2014; Engel et al., 2014; Johnson et al. 2015). Others have found that rising CO₂ levels can decrease the productivity of phytoplankton communities dominated by the coccolithophore *Emiliania huxleyi* (Delille et al., 2005;

Riebesell et al., 2017). Paradoxically, an increase in CO₂ concentrations from 385 to 800 μ atm decreased the productivity of surface phytoplankton assemblages dominated by diatoms in the South China Sea under natural fluctuating solar radiation (Gao et al., 2012). These discrepancies highlight the fact that the effects of rising CO₂ on C-fixation are dependent on algal community composition as well as regional environmental conditions (Egge et al., 2009; Gao et al., 2012; Celis-Pla et al. 2015; Holding et al., 2015; Hoppe et al., 2018).

On a global scale, by using satellite records and in situ monitoring, rising temperatures have been shown to reduce phytoplankton productivity in the open ocean (Boyce et al., 2010; Siegel et al., 2013), because increased thermal stratification of the water column can starve the algae of nutrients (Doney et al., 2006; Kletou and Hall-Spencer, 2012). In general, it seems that photosynthetic C-fixation increases with increasing temperature, reaches a maximum and decreases thereafter (Beardall and Raven, 2004). Optimal temperatures for C-fixation differ between latitudes and seasons, with small phytoplankton species functioning optimally at higher temperatures than larger species (Daufresne et al., 2009; Finkel et al., 2010; Sommer et al., 2015; Wolf et al., 2017). Carbon fixation was reduced when temperatures were experimentally increased in cold adapted phytoplankton assemblages (Wohlers et al., 2009; Wolf et al., 2017). However, increases from 27 °C to 30 °C enhanced photosynthetic C-fixation in incubations of samples of surface phytoplankton assemblages from two stations off China (Gao et al., 2017). Regional differences in physicochemical conditions may drive different responses of phytoplankton to ocean

climate change.

Temperature affects cellular membrane permeability, cell size of a single phytoplankton cell and the uptake of dissolved inorganic carbon (Beardall and Raven, 2004) and so has fundamental control over the effects of changing carbonate chemistry on photosynthetic C-fixation. For example, when CO₂ concentrations were increased from 390 to 690 µatm, C-fixation of a phytoplankton community at 12 °C (in situ temperature) decreased in the North Atlantic spring bloom area, whereas at 16 °C rising CO₂ levels enhanced C-fixation (Feng et al., 2009). Increasing CO₂ levels (from 150 to 300 µatm) combined with rising temperature (from –1 °C to 7 °C) synergistically enhanced phytoplankton productivity in the European Arctic Ocean, and the positive effect of rising CO₂ on productivity was lower at 6 °C than at 1 °C (Holding et al., 2015). Furthermore, elevated temperature reversed the positive effect of rising CO₂ on phytoplankton assemblages off Svalbard and did not affect the response of phytoplankton primary productivity in coastal Arctic and subarctic seawater to rising CO₂ (Coello-Camba et al., 2014; Hoppe et al., 2018). These results show that rising temperature and increasing CO₂ can have synergistic or antagonistic effects on the productivity of marine phytoplankton assemblages. Given that the carbon cycle underpins the ecology and fisheries productivity of marine ecosystems, region-specific research is urgently needed to assess whether rising atmospheric CO₂ levels will positively or negatively affect photosynthetic production.

In this work, we performed shipboard incubations at two coastal and two off-shore stations in the western South China Sea in autumn 2017 and measured photosynthetic

C-fixation rates and Chlorophyll *a* (Chl *a*) concentrations. Our aim was to assess how rising levels of pCO₂ and temperature are likely to affect coastal and offshore productivity in the South China Sea.

2. Materials and methods

2.1. Sampling and culture condition

This study was carried out aboard RV ‘Shiyan III’ in off-shore and coastal waters of the South China Sea from 11th September to 12th October, 2017 (Fig. 1). Surface seawater (0–2 m) was collected with a 8 L acid-cleaned plastic bucket and stored in a 30 L acid-cleaned polycarbonate tank at 9:00 a.m. to 10:00 a.m., at station S1 (12.99° N, 113.50° E) on September 21, station S2 (14.01 ° N, 113.01 ° E) on September 22, station S3 (17.75 ° N, 110.65 ° E) on October 2, and station S4 (18.30° N, 111.29° E) on October 3, respectively. Surface seawater at each station was filtered through a 200 µm mesh, and then dispensed into twelve 2 L Nalgene bottles. 1 µmol L⁻¹ NaNO₃ and 0.5 µmol L⁻¹ NaH₂PO₄ was added into the seawater in all treatments to stimulate phytoplankton growth (Chen et al., 2004; Tseng et al., 2005; Celis-Plá et al., 2015).

Six bottles for ambient temperature treatment were put into one deck incubator (120 cm × 85 cm × 25 cm) bathed with flowing surface seawater. Six bottles for the elevated temperature treatment were put into another deck incubator with an auto-temperature control system (Fig. S1) which fitted with two circulating coolers (AL36G-160, Shenzhen Aolinghengye Ltd., China) during the day, and heated at

night (Aqua Zonic, Shanghai AiKe Ltd., China). Temperatures in both incubators were measured hourly (Fig. 2A). Bottles were held in place using wire mesh with a pore size of 11.5 cm (Fig. S1). Three bottles of seawater in each incubator were bubbled with filtered (PVDF 0.22 μm pore size, simplepure, Haining) ambient air ($\sim 400 \mu\text{atm}$) or air of elevated CO_2 ($\sim 1,000 \mu\text{atm}$) during the incubation periods, respectively. The high CO_2 concentration was controlled using a CO_2 enricher (CE100B, Wuhan Ruihua Instrument & Equipment Ltd., China). An Eldonet broadband filter radiometer (ELDONET, Real Time Computer, Germany) was used to measure the incident solar radiation (Fig. 2B), and solar light intensities and weather condition were similar during the incubation periods. The positions of the bottles were changed three times per day to ensure they were exposed equally to sunlight. Our four treatments were: low temperature and low CO_2 (LTLC), low temperature and high CO_2 (LTHC), high temperature and low CO_2 (HTLC), high temperature and high CO_2 (HTHC). Each treatment had three replicates and the incubations were run for 6 days.

2.2. pH_{nbs} , total alkalinity and nutrient concentrations measurements

pH_{nbs} (NBS scale) was measured before incubation, 24 hrs after incubation and at the end of the 6 days experiment. At about 10:00 a.m., 20 mL samples for pH_{nbs} measurements were taken from the bottles and measured immediately at 25 $^{\circ}\text{C}$ with a pH meter (Benchtop pH, Orion 8102BN) calibrated with an equimolar pH buffer (Tris $\cdot\text{HCl}$, Hanna) which is isosmotic with seawater (Dickson, 1993). Total alkalinity (TA) was measured before incubation and at the end of the incubation. At 10:00 a.m. to

10:30 a.m., 100 mL samples for TA measurements were filtered (GF/F filter) by gentle pressure with 200 mbar in the pump (GM-0.5A, JINTENG). 100 μ L saturated HgCl₂ solution was added into the TA samples which were stored at 4 °C. TA was measured at 25 °C in the laboratory by potentiometric titration (AS-ALK1+, Apollo SciTech) according to Dickson et al. (2003). Carbonate chemistry parameters were calculated from TA, pH_{nbs}, phosphate, silicate, temperature, and salinity using the CO2SYS (Pierrot et al., 2006).

At the beginning of the incubation, dissolved inorganic nitrogen (DIN) and phosphate (DIP) concentrations of seawater in situ were obtained from the dataset of this cruise. At the end of the incubation, at 10:30 a. m. to 11:00 a. m., 50 mL samples for determination of DIN and DIP concentrations were syringe-filtered (0.22 μ m pore size, Haining), stored at –20 °C, measured using a scanning spectrophotometer (Du 800, Beckman Coulter) in the laboratory after the nitrate had been reduced to nitrite according to Hansen and Koroleff (1999).

2.3. Chlorophyll *a* analysis

At each station, at about 14:00 p.m., 2 L surface seawater were filtered onto a GF/F glass filter (25 mm, Whatman) for in situ chlorophyll *a* (Chl *a*) measurement. At the end of incubation, at 11:00 a.m to 12:00 a.m., 700 mL samples were filtered onto GF/F glass filters, and all filters were stored at –20 °C until they were analyzed in the laboratory. The filters were placed in 5 mL 100% methanol and stored at 4 °C for 12 hours. Then the solutions were centrifuged at 5000 g for 10 min and the absorbances

of the supernatant were determined using a scanning spectrophotometer (Du 800, Beckman Coulter). Chl *a* concentrations were determined as follows: $\text{Chl } a = 13.27 \times (A_{665} - A_{750}) - 2.68 \times (A_{632} - A_{750})$ ($\mu\text{g mL}^{-1}$) (Ritchie, 2002). A_{632} , A_{665} , and A_{750} represent absorbances of the supernatant at 632 nm, 665 nm and 750 nm.

2.4. Primary productivity measurements

Primary productivity was obtained according to the method described by Gao et al. (2017). On the final day of the incubations, at about 5:00 a.m., subsamples were taken from each incubation bottle, dispensed into two 50 mL quartz tubes placed under a plastic plate which allowed 85% PAR and non UVR transmissions, assuring that the light environment was similar to that of incubations. 5 μCi (0.185 MBq) $\text{NaH}^{14}\text{CO}_3$ (ICN Radiochemical, USA) was added to the subsamples, which were cultured in the corresponding deck incubators for 12 hrs (from 6:00 a.m. to 6:00 p.m.) and 24 hrs (from 6:00 a.m. to 6:00 a.m. next day) under solar radiation. Subsamples were then filtered onto GF/F glass filters, which were darkly stored at -20°C until they were analyzed in the laboratory. Each filter was put into a 10 mL scintillation vial, fumed with HCl for 24 hours to remove inorganic carbon, and dried at 60°C for 12 hrs. 3 mL scintillation cocktail (Hisafe 3, Perkin Elmer, Shelton, USA) was added to the vial and the activity of the fixed radiocarbon was measured using a liquid scintillation counting (LS 6500, Beckman Coulter, USA). The activity of photosynthetic C-fixation during 12 hrs incubation was defined to be the day-time primary productivity (DPP), and the photosynthetic C-fixation during 24 hours was considered

to be the net primary productivity (NPP) (Delille et al., 2005). The difference between DPP and NPP was taken as night time respiratory C loss.

2.5. Data analysis

Effects of temperature, CO₂ and their interactions on Chl *a*, DPP, NPP and night time respiration rates were assessed by a two-way analysis of variance (ANOVA). The normal distribution of all data was assessed by a Shapiro-Wilk's test, and homogeneity of variance was determined by a Levene's test. A Tukey Post hoc test (Tukey HSD) was performed to show difference between temperature or CO₂ treatments. Statistical analysis was tested by using R and significant difference was indicated by $p < 0.05$.

3 Results

3.1. Incubation temperature, nutrient concentrations and carbonate chemistry parameters

Incubation temperatures varied from 29.1 °C to 31.2 °C in our low temperature treatment (to match the surface seawater temperature at the time of sampling); and varied from 30.6 °C to 34.0 °C in our high temperature treatments (Fig. 2A). Average temperatures were 29.7 ± 0.29 °C for the low temperature treatments and 31.5 ± 0.41 °C for the high temperature treatments, respectively.

Dissolved inorganic nitrogen (DIN) and phosphate (DIP) concentrations in situ

surface water of the South China Sea were 0.03–0.12 $\mu\text{mol L}^{-1}$ and 0.14–0.21 $\mu\text{mol L}^{-1}$, respectively (Table 1). By adding NaNO_3 and NaH_2PO_4 to the seawater, DIN and DIP concentrations at the beginning of the incubation were 1.03–1.12 $\mu\text{mol L}^{-1}$ and 0.64–0.71 $\mu\text{mol L}^{-1}$, respectively. DIN concentrations at all treatments decreased below the detection limit ($< 0.04 \mu\text{mol L}^{-1}$) and DIP concentrations were about 0.05 $\mu\text{mol L}^{-1}$ at the end of the experiments. This means that DIN and DIP concentrations appeared to be replete at the beginning of incubations, and low DIN concentration could have limited the phytoplankton abundance at the end of incubations.

CO_2 concentrations were 354–439 μatm at low CO_2 levels and were 804–1059 μatm at high CO_2 levels (Table 2). Correspondingly, pH_{nbs} values were 8.17–8.25 at low CO_2 levels, and 7.85–7.95 at high CO_2 levels. Total alkalinities ranged 2319–2381 $\mu\text{mol L}^{-1}$ in all treatments.

3.2. Chl *a* concentration

Chl *a* concentrations in situ were 0.080 $\mu\text{g L}^{-1}$ at station S1, 0.091 $\mu\text{g L}^{-1}$ at station S2, 0.130 $\mu\text{g L}^{-1}$ at station S3, and 0.092 $\mu\text{g L}^{-1}$ at station S4 (Fig. 3). At the end of the incubation, temperature and CO_2 concentration did not significantly affect Chl *a* concentrations at stations S1 and S2, individually and interactively (Table S1; Fig. 3A,B). Elevated temperature significantly reduced Chl *a* concentrations at station S3 at both LC and HC levels (Tukey HSD, both $p < 0.05$), and at station S4 at LC level (Tukey HSD, $p = 0.02$) (Table S1; Fig. 3C,D). By the sixth day of the incubation, Chl *a* concentrations at station S3 were 47%–55% lower at HT than at LT (Tukey HSD, p

< 0.05) (Fig. 3C). At LC level, Chl *a* concentration at station S4 reduced by 52% with rising temperatures, while at HC Chl *a* concentration was not significantly affected by rising temperatures (Tukey HSD, $p = 0.7$) (Fig. 3D).

3.3. Day-time primary productivity

On the final day of the incubations, temperature and CO₂ concentration interactively affected day-time primary productivity at stations S1 and S2, but not at stations S3 and S4 (Table S1). Compared to low temperature and low CO₂ (LTLC) treatments, daytime productivity at station S1 was 41% higher at LTHC (Tukey HSD, $p = 0.02$) and 44% higher at HTLC (Tukey HSD, $p = 0.01$) (Fig. 4A). At station S2, daytime primary productivity was 12% higher at LTHC (Tukey HSD, $p = 0.08$) and 39% higher at HTLC (Tukey HSD, $p = 0.04$) than at LTLC. Daytime productivity at stations S1 and S2 was similar between LTLC and HTHC treatments (Tukey HSD, $p > 0.1$). At stations S3 and S4, daytime productivity was not significantly different between all treatments (Tukey HSD, all $p > 0.05$) (Fig. 4C,D).

3.4. Net primary productivity

On the final day of the incubations, at station S1, net primary productivity was lower at LTLC than at LTHC or HTLC conditions (Tukey HSD, $p = 0.3$ between LTLC and LTHC treatments; $p = 0.04$ between LTLC and HTLC treatments) (Fig. 5A). Net primary productivity was not significantly different between LTLC and HTHC treatments at station S1. Similarly, at station S2, net primary productivity at

LTLC was significantly lower than at HTLC (Tukey HSD, $p = 0.03$), whereas it was not significantly different between LTLC, LTHC and HTHC (Tukey HSD, all $p > 0.05$) (Fig. 5B). At stations S3 and S4, net primary production did not differ between all treatments (Tukey HSD, all $p > 0.05$) (Fig. 5C,D).

3.5. Night time respiration

Temperature and CO₂ concentration independently and interactively affected night time respiration rate at station S4, but not at the other stations (Table S1). At S1 and S2, at ambient temperature, night time respiration rates increased significantly at elevated CO₂ (Tukey HSD, both $p < 0.05$, Fig. 6A,B); whereas at high temperature, night time respiration rates were not affected by elevated CO₂ levels (Tukey HSD, both $p > 0.05$). At station S3, at HC, night time respiration rate was enhanced by rising temperature (Tukey HSD, $p = 0.03$) (Fig. 6C); at station S4, at LC, night time respiration rate was enhanced by rising temperature (Tukey HSD, $p < 0.01$) (Fig. 6D).

4 Discussion

Warming and increased CO₂ levels both individually boosted primary productivity in samples of phytoplankton communities taken in nearshore and offshore habitats in the western South China Sea, although these were not all statistically significant increases (Figs. 4; 5). The effect of rising CO₂ on primary productivity and respiration was temperature dependent, and the combination of elevated CO₂ and temperature

287 resulted in antagonistic effects on production and respiration of the phytoplankton
288 assemblages (Figs. 4; 5; 6).

289 There were enhanced carbon fixation rates at elevated CO₂ levels at all stations
290 (Figs. 4; 5), a similar result to that obtained in other experiments using shipboard
291 incubations, mesocosm experiments and CO₂ seeps (Tortell et al., 2008; Engel et al.,
292 2014; Holding et al., 2015; Johnson et al., 2015). The dominant phytoplankton groups
293 at our offshore stations were *Synechococcus*, *Prochlorococcus* and picoeukaryotes
294 (Zhong et al., 2013; Wu et al., 2014a) whereas diatoms (*Pseudonitzschia pungens* and
295 *Chaetoceros pseudocurvisetus*) and dinoflagellates (*Protoperdinium conicum*) dominated at
296 our inshore stations (Zhang et al., 2014). Rising seawater CO₂ levels are expected to
297 increase carbon fixation rates of larger species more than small phytoplankton species
298 because it is more difficult for large species to take up sufficient inorganic carbon as
299 they have a smaller cell surface:volume quotient (Wu et al., 2014b). Furthermore,
300 elevated CO₂ levels tend to increase the percentage of diatoms in phytoplanktonic and
301 sessile algal communities (Tortell et al., 2002; Domingues et al., 2014). In our
302 experiments, the different responses of offshore and inshore surface phytoplankton
303 assemblages to increased levels of temperature and pCO₂ could be due to differences
304 in the phytoplankton communities.

305 Temperature increases of about 2°C significantly increased phytoplankton
306 assemblage productivity in coastal water at ambient levels of CO₂. This can be
307 expected, since warming is known to increase enzyme activity, and enhance cellular
308 metabolic activity and so improve nutrient or CO₂ uptake (Montagnes and Franklin,

2001; Beardall and Raven, 2004). However, warming did not lead to any increase in night time respiration in coastal water, which might indicate less effect of rising temperature on enzyme activity in our study (Fig. 6), suggesting that increased productivity may be due to more efficient nutrient or CO₂ uptake. Another possible reason for greater primary productivity in the warming treatments may be a shift from predominantly large to mainly small sized algal cells during the incubation (Daufresne et al. 2009; Sommer et al. 2015). Unfortunately, we did not determine the community structure at the end of experiments. However, both ambient and elevated temperature treatments in this study are close to the upper thermal limit for growth of most phytoplankton species (Boyd et al. 2013). In this case, rising temperature is expected to shift community composition and cause an increase in the abundance of small-celled phytoplankton. Small species show stronger temperature responses in terms of their photosynthetic C-fixation compared with large species (Sommer et al., 2015), which may lead to higher productivity in warmer coastal water (Figs. 4, 5).

In the present work, we observed higher night respiratory under HC conditions (Fig. 6) in coastal waters at ambient temperature, this could be due to enhanced energy demand against the acidic stress such as maintaining the cell's homeostasis (Jin et al. 2015). However, such a respiratory enhancement was not observed at elevated temperature. It is possible that such a level of elevated temperature may increase cellular metabolic activity and periplasmic redox activity that counter-acted the acidic stress. On the other hand, small-sized species seem insensitive to increased pCO₂ in terms of carbon fixation (Tortell et al. 2002; Domingues et al., 2014; Wu et

al., 2014b), and they are highly sensitive to high light intensities that cause severe inhibition of C-fixation (Li et al., 2011). Therefore, these effects might contribute to the observed similar response in primary productivity of offshore-water where small-sized species dominated (Zhong et al., 2013), and also contribute to the low primary productivity of coastal water at warming and acidification treatments with high percentage of small sized species (Figs 4, 5). Gao et al. (2012) reported that rising CO₂ decreased phytoplankton productivity in surface seawater under 90% incident solar radiation in the South China Sea, due to enhanced photoinhibition. Different nutrient concentrations can be responsible for the discrepancy between our study and Gao et al., (2012), because seawater was enriched by 1 µmol L⁻¹ NaNO₃ and 0.5 µmol L⁻¹ NaH₂PO₄ in this study whereas initial DIN and DIP concentration were lower than 0.01 µmol L⁻¹ and 0.15 µmol L⁻¹, respectively, in the study of Gao et al. (2012). Rising CO₂ is known to increase primary productivity at high nutrient concentrations, but the additional inorganic carbon does not boost productivity in nutrient limited conditions (Yoshimura et al., 2009; Celis-Plá et al., 2015).

The temperature and CO₂ concentrations of surface oceans are rising simultaneously, but the carbonate chemistry of coastal water is complex, due to the local effects of hydrography, metabolic activity, nutrient input and watershed processes (Duarte et al. 2013). The effects of CO₂ on phytoplankton physiology and productivity has important biogeochemical implications. Increased productivity at elevated CO₂ level could accelerate carbon sequestration of phytoplankton which may increase the CO₂ uptake of coastal seawater from the atmosphere. Decreased

chlorophyll concentrations offshore due to warming may limit biological productivity because phytoplankton are the primary energy source for marine food chains. Our study shows that phytoplankton assemblages in different regions respond differently to increases in CO₂ and temperature. However, if our shipboard tests reflect natural responses, then ongoing warming and acidification in the South China Sea is not expected to increase overall regional primary productivity due to a lack of nutrients in offshore waters. Other environmental factors such as changes in solar radiation, wind-speed induced mixing and deposition of dusts may also affect the primary productivity of phytoplankton communities. Therefore, shipboard incubations during different seasons or with waters influenced by episodic events might lead to differential responses to warming and acidification.

5. Conclusion

The present study shows combined effects of ocean warming and acidification on phytoplankton primary productivity, Chl *a* concentration and night respiration of two coastal and two offshore waters in the western South China Sea. Warming and elevated CO₂ levels individually increased primary productivity, especially in the coastal water. However, the combination of elevated temperature and increased CO₂ did not increase primary productivity at all stations. Different responses in primary productivity, Chl *a* concentration and night respiration to warming and acidification between the coastal and offshore waters may be due to differences in the phytoplankton community composition and in their sensitivity to elevated temperature

or CO₂ levels.

Acknowledgements

This study was supported by National Natural Science Foundation (41720104005, 41721005, 41430967, 41806129) and Joint Project of National Natural Science Foundation of China and Shandong Province (No. U1606404), China Postdoctoral Science Foundation (2017M612129) and the outstanding postdoctoral program of State Key Laboratory of Marine Environmental Science (Xiamen University). We thank the captain and crew of the research vessel Shiyan III and the chief Dr. Zhen Shi for his organization during the cruises.

References

- Bach, L.T., Riebesell, U., Gutowska, M.A., Federwisch, L., Schulz, K.G., 2015. A unifying concept of coccolithophore sensitivity to changing carbonate chemistry embedded in an ecological framework, *Prog. Oceanogr.*, 135, 125–138.
- Beardall, J., Raven, J.A., 2004. Potential effects of global change on microalgal photosynthesis, growth and ecology. *Phycologia* 43: 26–40.
- Boyce, D.G., Lewis, M.R., Worm, B., 2010. Global phytoplankton decline over the past century. *Nature* 466, 591–596
- Boyd, P.W., Lennartz, S.T., Glover, D.M., Doney, S.C., 2015. Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Change* 5, 71–79.
- Boyd, P.W., Rynearson, T.A., Armstrong, E.A., Fu, F., Hayashi, K., Hu, Z., Hutchins, D.A., Kudela, R.M., Litchman, E., Mulholland, M.R., Passow, U., Strzepek, R.F., Whittaker, K.A., Yu, E., Thomas, M.K., 2013. Marine phytoplankton temperature versus growth responses from polar to tropical waters—outcome of a scientific community-wide study. *PLOS ONE* 8, e63091. doi: 10.1371/journal.pone.0063091.
- Brodie, J., Williamson, C.J., Smale, D.A., Kamenos, N.A., Mieszkowska, N., Santos, R., Cunliffe, M., Steinke, M., Yesson, C., Anderson, K.M., Asnaghi, V., Brownlee, C., Burdett, H.L., Burrows, M.T., Collins, S., Donohue, P.J.C., Harvey, B., Foggo, A., Noisette, F., Nunes, J., Ragazzola, F., Raven, J.A., Schmidt, D.N., Suggett, D., Teichberg, M., Hall-Spencer, J.M., 2014. The future of the NE

419 Atlantic benthic flora in a high CO₂ world. *Ecol. Evol.* 4, 2787–2789.

420 Caldeira, K., Wickett, M.E., 2003. Oceanography: anthropogenic carbon and ocean
421 pH. *Nature* 425, 365–365.

422 Celis-Plá, P.S.M., Hall-Spencer, J.M., Horta, P., Milazzo, M., Korbee, N., Cornwall,
423 C.E., Figueroa, F.L., 2015. Macroalgal responses to ocean acidification depend
424 on nutrient and light levels. *Front. Mar. Sci.* 2, 26.

425 Chen, Y.L., Chen, H.Y., Karl, D.M., Takahashi, M., 2004. Nitrogen modulates
426 phytoplankton growth in spring in the South China Sea. *Cont. Shelf Res.* 24,
427 527–541.

428 Coello-Camba, A., Agustí, S., Holding, J., Arrieta, J.M., Duarte, C.M., 2014.
429 Interactive effect of temperature and CO₂ increase in Arctic phytoplankton. *Front.*
430 *Mar. Sci.* 1, 49. doi: 10.3389/fmars.2014.00049

431 Daufresne, M., Lengfellner, K., Sommer, U., 2009. Global warming benefits the small
432 in aquatic ecosystems. *Proc. Natl. Acad. Sci. USA* 106, 12788–12793.

433 Delille, B., Harlay, J., Zondervan, I., Jacquet, S., Chou, L., Wollast, R., Bellerby, R.G.,
434 Frankignoulle, M., Borges, A.V., Riebesell, U., Gattuso, J.P., 2005. Response of
435 primary production and calcification to changes of *p*CO₂ during experimental
436 blooms of the coccolithophorid *Emiliana huxleyi*. *Global Biogeochem. Cy.* 19,
437 GB2023. doi: 10.1029/2004GB002318.

438 Dickson, A.G., 1993. pH buffers for sea water media based on the total hydrogen ion
439 concentration scale. *Deep Sea Res.* 40, 107–118.

440 Dickson, A.G., Afghan, J.D., Anderson, G.C., 2003. Reference materials for oceanic

CO₂ analysis: a method for the certification of total alkalinity. *Mar. Chem.* 80,
185–197.

Domingues, R.B., Guerra, C., Barbosa, A.B., Brotas, V., Galvão, H.M., 2014. Effects
of ultraviolet radiation and CO₂ increase on winter phytoplankton assemblages in
a temperate coastal lagoon. *J. Plankton Res.* 36: 672–684.

Doney, S.C., 2006. Phytoplankton in a warmer world. *Nature* 444, 695–696.

Duarte, C.M., Hendriks, I.E., Moore, T.S., Olsen, Y.S., Steckbauer, A., Ramajo, L.,
Carstensen, J., Trotter, J.A., McCulloch, M., 2013. Is ocean acidification an
open-ocean syndrome? Understanding anthropogenic impacts on seawater pH.
Estuar. Coast. 36, 221–236.

Egge, J.K., Thingstad, T.F., Larsen, A., Engel, A., Wohlers, J., Bellerby, R.G.J.,
Riebesell, U., 2009. Primary production during nutrient-induced blooms at
elevated CO₂ concentrations. *Biogeosciences* 6: 877–885.

Engel, A., Piontek, J., Grossart, H.P., Riebesell, U., Schulz, K.G., Sperling, M., 2014.
Impact of CO₂ enrichment on organic matter dynamics during nutrient induced
coastal phytoplankton blooms. *J. Plankton Res.* 36, 641–657.

Falkowski, P.G., Raven, J.A., 2007. *Aquatic Photosynthesis* Second Edition.
Princeton University Press, USA.

Feng, Y., Hare, C.E., Leblanc, K., Rose, J.M., Zhang, Y., DiTullio, G.R., Lee,
P.A., Wilhelm, S.W., Rowe, J.M., Sun, J., Nemcek, N., Gueguen, C., Passow, U.,
Benner, I., Brown, C., Hutchins, D.A., 2009. Effects of increased pCO₂ and
temperature on the North Atlantic spring bloom. I. The phytoplankton

community and biogeochemical response. Mar. Ecol. Prog. Ser. 388, 13–25.

Finkel, Z.V., Beardall, J., Flynn, K.J., Quigg, A., Rees, T.V., Raven, J.A., 2010. Phytoplankton in a changing world: cell size and elemental stoichiometry. J. Plankton Res. 32: 119–137.

Gao, G., Jin, P., Liu, N., Li, F., Tong, S., Hutchins, D.A., Gao, K., 2017. The acclimation process of phytoplankton biomass, carbon fixation and respiration to the combined effects of elevated temperature and $p\text{CO}_2$ in the northern South China Sea. Mar. Poll. Bull. 118, 213–220.

Gao, K., Xu, J., Gao, G., Li, Y., Hutchins, D.A., Huang, B., Wang, L., Zheng, Y., Jin, P., Cai, X., Häder, D.P., Li, W., Xu, K., Liu, N.N., Riebesell, U., 2012. Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. Nat. Clim. Chang. 2, 519–523.

Gao, K.S., Zheng, Y.Q., 2010. Combined effects of ocean acidification and solar UV radiation on photosynthesis, growth, pigmentation and calcification of the coralline alga *Corallina sessilis* (Rhodophyta). Global Change Biol. 16: 2388–2398.

Hansen, H.P., Koroleff, F., 1999. Determination of nutrients. In: Grasshoff, K., Kremling, K., Ehrhardt, M. (Eds.), Methods of seawater analysis. WILEY-VCH Publishers, 159–228.

Hare, C.E., Leblanc, K., DiTullio, G.R., Kudela, R.M., Zhang, Y., Lee, P.A., Riseman, S., Hutchins, D.A., 2007. Consequences of increased temperature and CO_2 for phytoplankton community structure in the Bering Sea. Mar. Ecol. Prog. Ser. 352,

485 9–16.

486 Holding, J.M., Duarte, C.M., Sanz-Martín, M., Mesa, E., Arrieta, J.M., Chierici, M.,
487 Hendriks, I., Garcia-Corral, L., Regaudie-de-Gioux, A., Delgado, A., 2015.
488 Temperature dependence of CO₂-enhanced primary production in the European
489 Arctic Ocean. *Nat. Clim. Chang* 5, 1079–1082

490 Hoppe, C.J.M., Wolf, K.K.E., Schuback, N., Tortell, P.D., Rost, B., 2018.
491 Compensation of ocean acidification effects in Arctic phytoplankton assemblages.
492 *Nat. Clim. Chang* 8, 529–533.

493 IPCC, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B:*
494 *Regional Aspects. Contribution of Working Group II to the Fifth Assessment*
495 *Report of the Intergovernmental Panel on Climate Change.* Cambridge Univ.
496 Press, New York.

497 Ji, X., Liu, G., Gao, S., Wang, H., Zhang, M., 2017. Comparison of air-sea CO₂ flux
498 and biological productivity in the South China Sea, East China Sea, and Yellow
499 Sea: a three-dimension physical-biogeochemical modeling study. *Acta Oceanol.*
500 *Sin.* 36, 1–10.

501 Jin, P., Wang, T., Liu, N., Dupont, S., Beardall, J., Boyd, P.W., Riebesell, U., Gao,
502 K.S., 2015. Ocean acidification increases the accumulation of toxic phenolic
503 compounds across trophic levels. *Nature Comm.* 6: 8714.

504 Johnson, V.R., Brownlee, C., Milazzo, M., Hall-Spencer, J.M., 2015. Microalgal
505 assemblage shift along a marine CO₂ gradient subjected to multiple
506 environmental stressors. *J. Mar. Sci. Eng.* 3, 1425–1447.

507 Kim, J.M., Lee, K., Shin, K., Kang, J.H., Lee, H.W., Kim, M., Jang, P.G., Jang, M.C.,
 508 2006. The effect of seawater CO₂ concentration on growth of a natural
 509 phytoplankton assemblage in a controlled mesocosm experiment. *Limnol.*
 510 *Oceanogr.* 51, 1629–1636.

511 Kletou, D., Hall-Spencer, J.M., 2012. Threats to ultraoligotrophic marine ecosystems.
 512 In Cruzado A (ed): *Marine Ecosystems*. In Tech - Open Access Publisher.
 513 ISBN 979-953-307-430-5.

514 Li, G., Gao, K., Gao, G., 2011. Differential impacts of solar UV radiation on
 515 photosynthetic carbon fixation from the coastal to offshore surface waters in the
 516 South China Sea. *Photochem. Photobio.* 87, 329–334.

517 Liu, N., Beardall, J., Gao, K., 2017. Elevated CO₂ and associated seawater chemistry
 518 do not benefit a model diatom grown with increased availability of light. *Aquat.*
 519 *Microb. Ecol.* 79, 137–147.

520 Montagnes, D.J., Franklin, M., 2001. Effect of temperature on diatom volume, growth
 521 rate, and carbon and nitrogen content: reconsidering some paradigms. *Limnol.*
 522 *Oceanogr.* 46, 2008–2018.

523 Pierrot, D., Lewis, E., Wallace, D.W.R., 2006. MS Excel program developed for CO₂
 524 system calculations, ORNL/CDIAC-105, Carbon Dioxide Information Analysis
 525 Centre, Oak Ridge National Laboratory, U.S. Department of Energy.
 526 https://doi.org/10.3334/CDIAC/otg.CO2SYS_XLS_CDIAC105a.

527 Riebesell, U., Bach, L.T., Bellerby, R.G.J., Monsalve, J.R.B., Boxhammer, T., Czerny,
 528 J., Larsen, A., Ludwig, A., Schulz, K.G., 2017. Competitive fitness of a

529 predominant pelagic calcifier impaired by ocean acidification. *Nat. Geosci.* 10,
530 19–23.

531 Ritchie, R.J., 2006. Consistent sets of spectrophotometric chlorophyll equations for
532 acetone, methanol and ethanol solvents. *Photosyn. Res.* 89, 27–41.

533 Siegel, D.A., Behrenfeld, M.J., Maritorena, S., McClain, C.R., Antoine, D., Bailey,
534 S.W., Bontempi, P.S., Boss, E.S., Dierssen, H.M., Doney, S.C., 2013. Regional to
535 global assessments of phytoplankton dynamics from the SeaWiFS mission.
536 *Remote Sens. Environ.* 135, 77–91.

537 Sommer, U., Paul, C., Moustaka-Gouni, M., 2015. Warming and ocean acidification
538 effects on phytoplankton—from species shifts to size shifts within species in a
539 Mesocosm Experiment. *PLoS ONE* 10, e0125239,
540 doi:10.1371/journal.pone.0125239.

541 Taucher, J., Schulz, K.G., Dittmar, T., Sommer, U., Oschlies, A., Riebesell, U., 2012.
542 Enhanced carbon overconsumption in response to increasing temperatures during
543 a mesocosm experiment. *Biogeosciences* 9, 3531–3545.

544 Tortell, P.D., DiTullio, G.R., Sigman, D.M., Morel, F.M.M., 2002. CO₂ effects on
545 taxonomic composition and nutrient utilization in an Equatorial Pacific
546 phytoplankton assemblage. *Mar. Ecol. Prog. Ser.* 236, 37–43.

547 Tortell, P.D., Payne, C.D., Li, Y., Trimborn, S., Rost, B., Smith, W.O., Riesselman, C.,
548 Dunbar, R.B., Sedwick, P., DiTullio, G.R., 2008. CO₂ sensitivity of Southern
549 Ocean phytoplankton. *Geophys. Res. Lett.* 35, L04605, doi:
550 10.1029/2007GL032583.

551 Tseng, C.M., Wong, G.T.F., Lin, I.I., Wu, C.R., Liu, K.K., 2005. A unique seasonal
 552 pattern in phytoplankton biomass in low-latitude waters in the South China Sea.
 553 *Geophys. Res. Lett.* 32, L08608, doi: 10.1029/2004GL022111.

554 Wohlers, J., Engel, A., Zöllner, E., Breithaupt, P., Jürgens, K., Hoppe, H.G., Sommer,
 555 U., Riebesell, U., 2009. Changes in biogenic carbon flow in response to sea
 556 surface warming. *Proc. Natl. Acad. Sci. USA* 106, 7067–7072.

557 Wolf, K.K.E., Hoppe, C.J.M., Rost, B., 2017. Resilience by diversity: Large
 558 intraspecific differences in climate change responses of an Arctic diatom. *Limnol.*
 559 *Oceanogr.* 63, 397–411.

560 Wu, W., Huang, B., Liao, Y., Sun, P., 2014a. Picoeukaryotic diversity and distribution
 561 in the subtropical–tropical South China Sea. *FEMS Microbiol. Ecol.* 89,
 562 563–579.

563 Wu, Y., Campbell, D.A., Irwin, A.J., Suggett, D.J., Finkel, Z.V., 2014b. Ocean
 564 acidification enhances the growth rate of larger diatoms. *Limnol. Oceanogr.* 59,
 565 1027–1034.

566 Wu, H.Y., Zou, D.H., Gao, K.S., 2008. Impacts of increased atmospheric CO₂
 567 concentration on photosynthesis and growth of micro- and macro-algae. *Sci.*
 568 *China Ser. C-Life Sci.* 51: 1144–1150.

569 Yoshimura, T., Nishioka, J., Suzuki, K., Hattori, H., Kiyosawa, H., Watanabe, Y.W.,
 570 2009. Impacts of elevated CO₂ on phytoplankton community composition and
 571 organic carbon dynamics in nutrient-depleted Okhotsk Sea surface waters.
 572 *Biogeosci. Discuss.* 6, 4143–4163.

573 Zhang, G., Pang, Y., Chen, S., Wu, Z., Chen, D., Wang, D., Huang, B., 2014. Study on
574 the communities of the netz-phytoplankton in the coastal waters of Hainan Island
575 in the early summer. *Trans. Oceanol. Limnol.* 3, 97–104.

576 Zhong, C., Xiao, W., Huang, B., 2013. The response of phytoplankton to mesoscale
577 eddies in western South China Sea. *Adv. Mar. Sci.* 31, 213–220.

578

579

580

581

582

583

584

585

586

587

588

589

590

591

592

593

594

|

Figure Legend

Figure 1. Sampling stations in the western South China Sea in the cruise during autumn 2017.

Figure 2. Water temperature in the deck incubators for the low and high temperature treatments during the incubations, and solar radiation.

Figure 3. Chl *a* concentration of surface phytoplankton assemblages in situ and in the bottle after 6 days of incubation at different experiment conditions. Different letters indicated statistically difference based on Tukey post hoc test. The values represent the mean \pm standard deviation (error bar) for three replicates.

Figure 4. Daytime primary productivity (DPP) of surface phytoplankton assemblages in the bottle after 6 days of incubation at different experiment conditions. Different letters indicated statistically difference based on Tukey post hoc test. The values represent the mean \pm standard deviation (error bar) for three replicates

Figure 5. Net primary productivity (NPP) of surface phytoplankton assemblages in the bottle after 6 days of incubation at different experiment conditions. Different letters indicated statistically difference based on Tukey post hoc test. The values represent the mean \pm standard deviation (error bar) for three replicates

617

618 Figure 6. Night time respiration rate of surface phytoplankton assemblages in the
619 bottle after 6 days of incubation at different experiment conditions. Different letters
620 indicated statistically difference based on Tukey post hoc test. The values represent
621 the mean \pm standard deviation (error bar) for three replicates

622

623

624

625

626

627

628

629

630

631

632

633

634

635

636

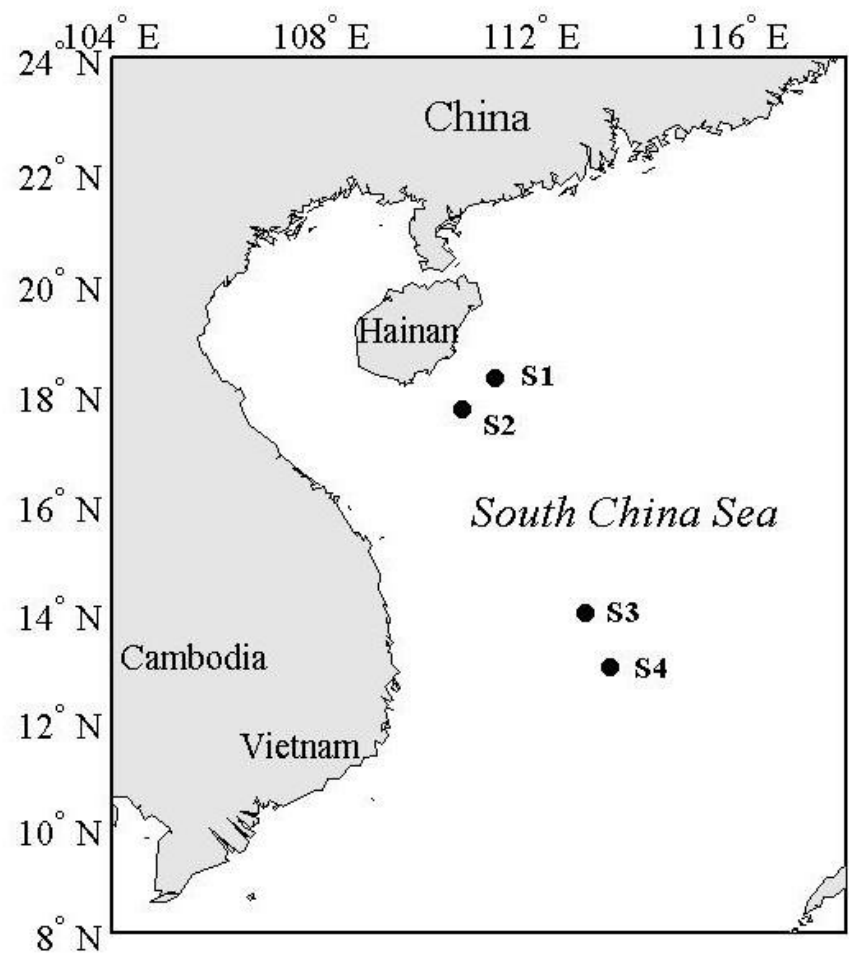
637

638

|

639

640



641

642

643

644 Figure 1

645

646

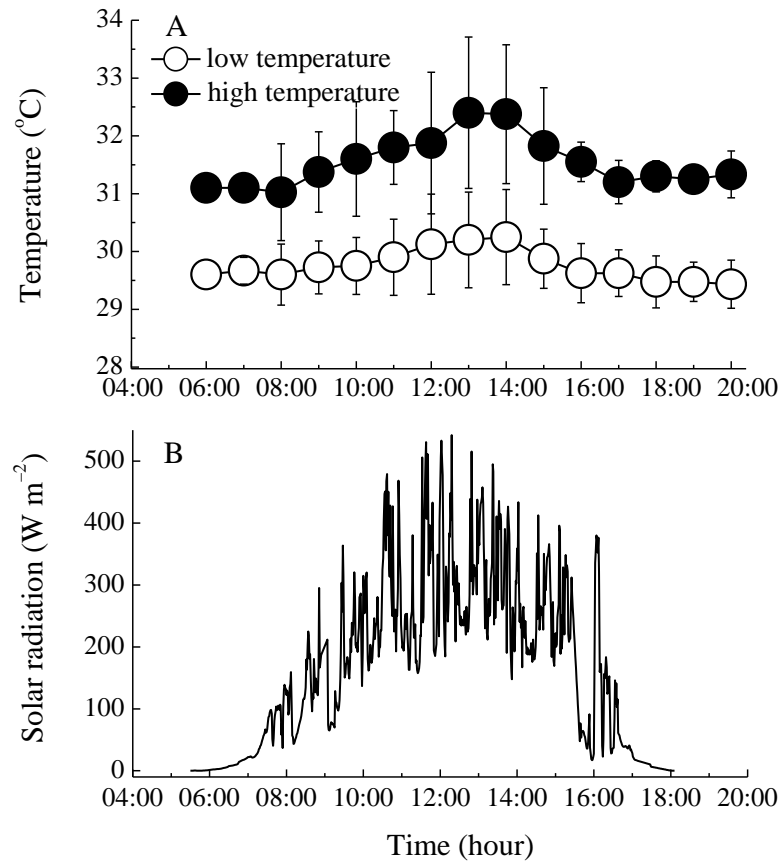
647

648

649

|

650



651

652

653

654 Figure 2

655

656

657

658

659

660

661

|

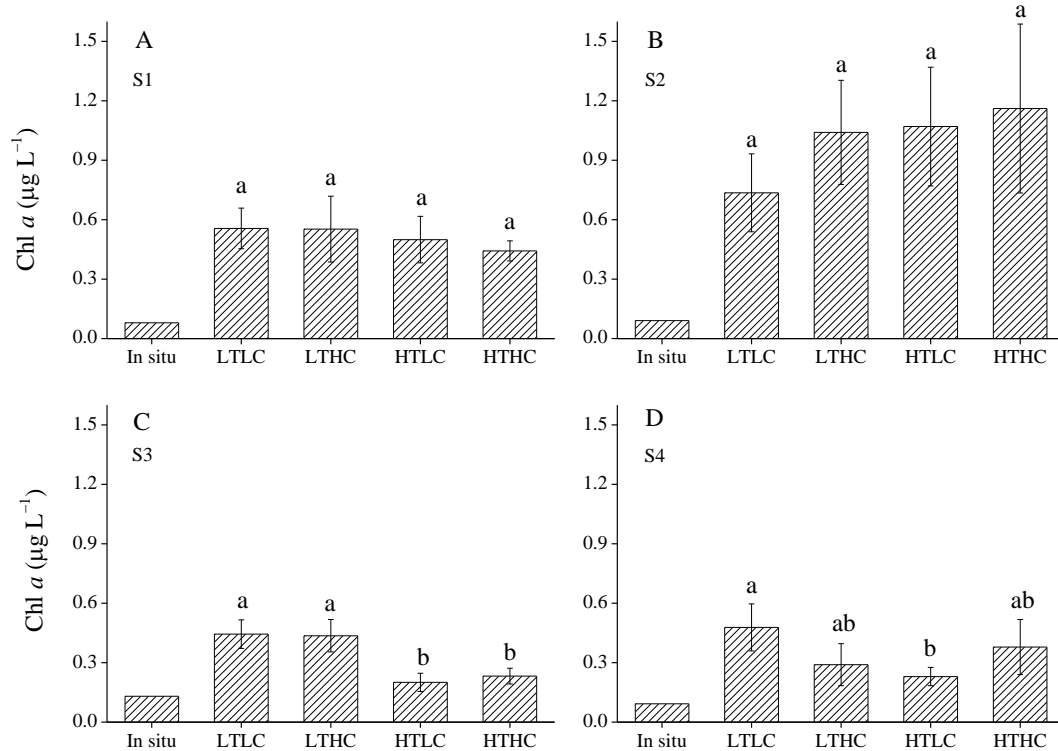


Figure 3

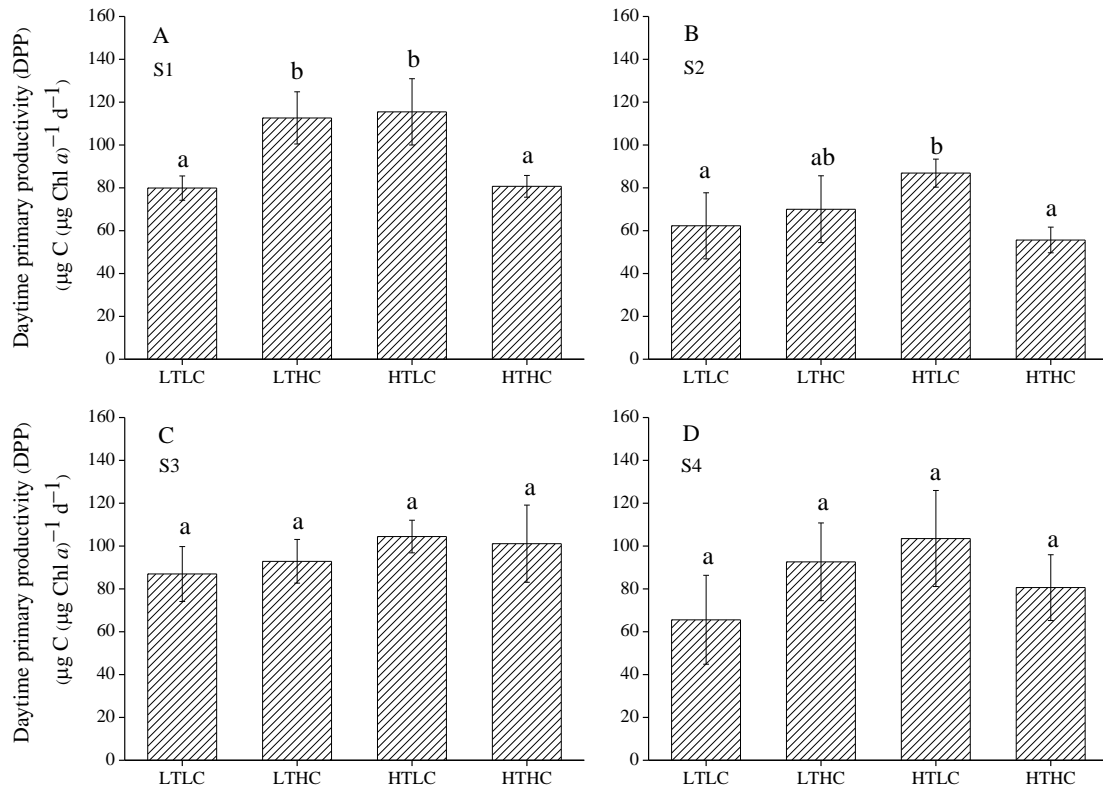


Figure 4

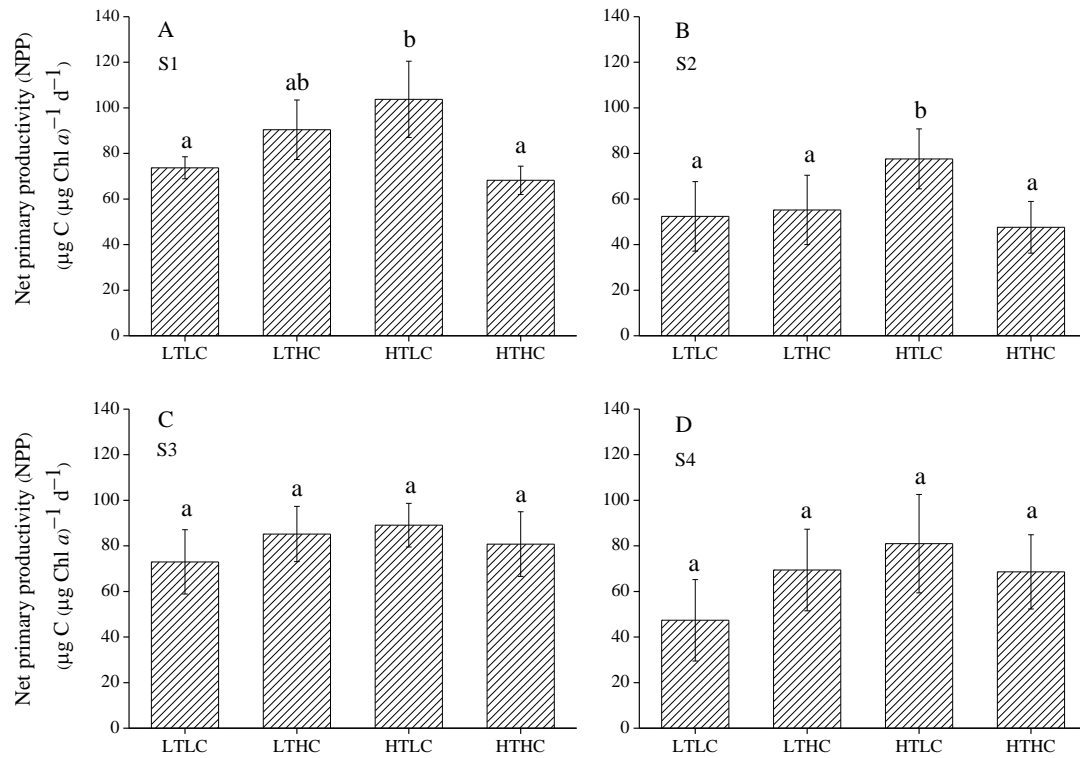


Figure 5

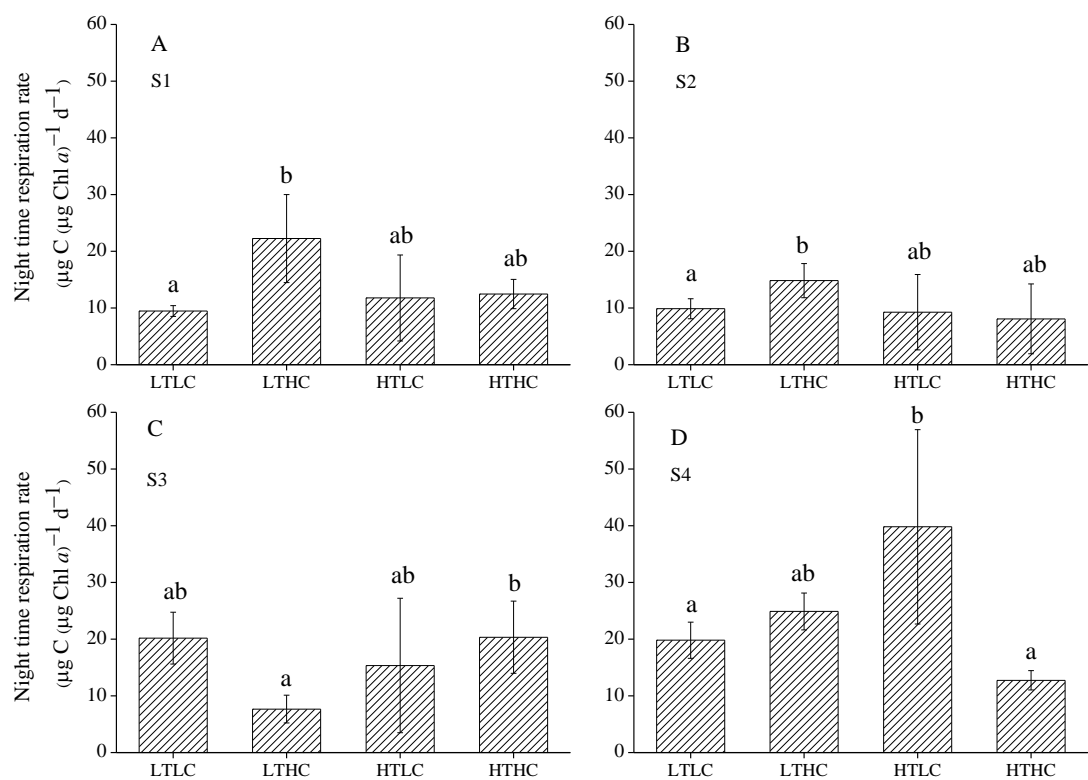


Figure 6

Table 1. Dissolved inorganic nitrogen (DIN) and phosphate (DIP) concentrations at the beginning and end of the incubation. 1 $\mu\text{mol L}^{-1}$ NaNO_3 and 0.5 $\mu\text{mol L}^{-1}$ NaH_2PO_4 was added into the seawater in the beginning of the incubation. Data in the bracket were DIN and DIP concentrations *in situ*. ND indicates that concentration was below the detection limit ($< 0.04 \mu\text{mol L}^{-1}$).

		DIN ($\mu\text{mol L}^{-1}$)	DIP ($\mu\text{mol L}^{-1}$)
S1	Before culture	1 (0.08)	0.5 (0.17)
	After culture	ND	0.05 \pm 0.01
S2	Before culture	1 (0.03)	0.5 (0.21)
	After culture	ND	0.04 \pm 0.02
S3	Before culture	1 (0.03)	0.5 (0.14)
	After culture	ND	0.05 \pm 0.01
S4	Before culture	1 (0.12)	0.5 (0.16)
	After culture	ND	0.05 \pm 0.01

Table 2. Carbonate chemistry parameters of the seawater in the final day of the incubations at different temperature and pCO₂ conditions. TA and pH samples were collected and measured. Different letters (a and b) indicated statistically difference based on Tukey post hoc test. pH_{nbs} means the pH measurements in seawater on the NBS scale.

	pCO ₂ (μatm)	pH _{nbs}	TA (μmol L ⁻¹)	DIC (μmol L ⁻¹)	HCO ₃ ⁻ (μmol L ⁻¹)	CO ₃ ²⁻ (μmol L ⁻¹)	CO ₂ (μmol L ⁻¹)	Ω calcite
LTLC	419±13 ^a	8.19±0.01 ^a	2342±15 ^a	2050±12 ^a	1818±11 ^a	220±5 ^a	12±0.4 ^a	5.5±0.1 ^a
LTHC	977±64 ^b	7.88±0.03 ^b	2349±18 ^a	2210±16 ^b	2060±17 ^b	121±7 ^b	28±1.8 ^b	3.0±0.2 ^b
HTLC	376±14 ^a	8.23±0.01 ^a	2343±16 ^a	2028±8 ^a	1782±7 ^a	235±8 ^a	11±0.4 ^a	5.8±0.2 ^a
HTHC	891±61 ^b	7.91±0.03 ^b	2348±22 ^a	2194±18 ^b	2038±18 ^b	130±8 ^b	26±1.8 ^b	3.2±0.2 ^b

Table S1. Results of two-way ANOVAs of the effects of temperature and $p\text{CO}_2$ on Chl a , day-time primary productivity (DPP), net primary productivity (NPP) and night time respiration rate. Temp indicates temperature and significant difference was setup to $p < 0.05$.

Station	Parameter	Treatment	df	F-value	p
S1	Chl a	Temp	1	2.80	0.13
		CO ₂	1	0.30	0.61
		Temp \times CO ₂	1	0.14	0.71
	DPP	Temp	1	2.38	0.15
		CO ₂	1	0.68	0.43
		Temp \times CO ₂	1	31.53	<0.01
	NPP	Temp	1	1.65	0.21
		CO ₂	1	0.14	0.75
		Temp \times CO ₂	1	14.77	<0.01
	Respiration	Temp	1	1.36	0.26
		CO ₂	1	4.43	0.07
		Temp \times CO ₂	1	3.56	0.09
S2	Chl a	Temp	1	2.43	0.15
		CO ₂	1	2.20	0.18
		Temp \times CO ₂	1	0.38	0.53
	DPP	Temp	1	0.006	0.94
		CO ₂	1	20.74	<0.01
		Temp \times CO ₂	1	7.62	<0.05
	NPP	Temp	1	0.37	0.57
		CO ₂	1	4.03	0.08
		Temp \times CO ₂	1	3.98	0.08
	Respiration	Temp	1	0.92	0.37
		CO ₂	1	4.65	0.06
		Temp \times CO ₂	1	1.16	0.31
S3	Chl a	Temp	1	38.58	<0.01
		CO ₂	1	0.67	0.41
		Temp \times CO ₂	1	0.32	0.61
	DPP	Temp	1	2.43	0.17
		CO ₂	1	0.02	0.93
		Temp \times CO ₂	1	0.34	0.59
	NPP	Temp	1	0.88	0.39
		CO ₂	1	0.050	0.82
		Temp \times CO ₂	1	1.77	0.21
	Respiration	Temp	1	1.52	0.20
		CO ₂	1	0.14	0.71

S4	Chl <i>a</i>	Temp × CO ₂	1	1.03	0.34
		Temp	1	7.53	<0.05
		CO ₂	1	0.005	0.95
	DPP	Temp × CO ₂	1	7.53	<0.05
		Temp	1	0.39	0.55
		CO ₂	1	0.0001	0.99
	NPP	Temp × CO ₂	1	5.45	<0.05
		Temp	1	1.64	0.23
		CO ₂	1	0.46	0.56
	Respiration	Temp × CO ₂	1	2.50	0.16
		Temp	1	17.01	<0.05
		CO ₂	1	17.97	<0.05
Temp × CO ₂		1	28.04	<0.05	

753

754

755

756

757

758

759

760

761

762

763

764

765

766

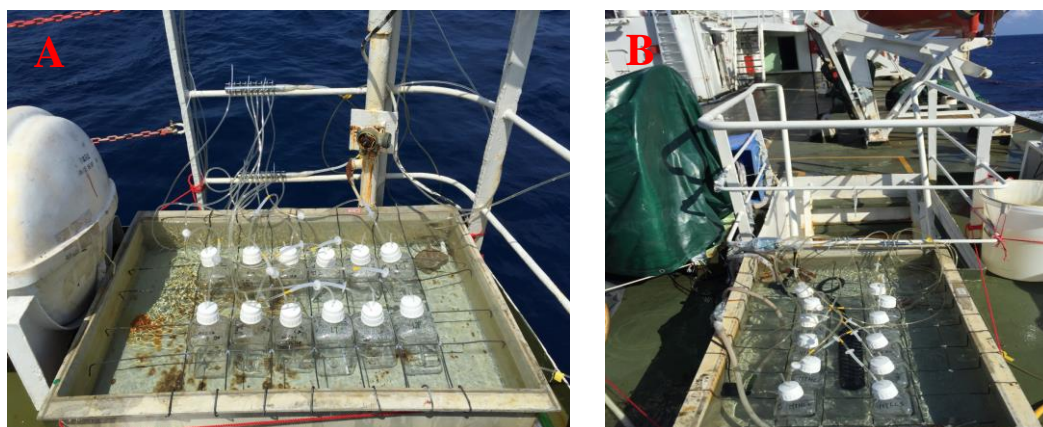
767

768

|

769

770



771

772

773

774 Figure S1. Phytoplankton assemblages were cultured at low temperature (in situ
775 temperature, A) and high temperature (in situ + 1.8 °C, B) treatments.

776

777

778

779